Dimensional Coherence Collapse Predicts Late-Stage Hardening in Black Hole Evaporation

Example Paper - Contains Simulated Data

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Preprint version 1.0

Abstract

Black hole evaporation, as originally predicted by Hawking, leads to thermal radiation emission but raises unresolved questions about information loss and the quantum structure of spacetime. We propose a thermodynamic extension of black hole evaporation dynamics based on the Coherence Equation $H_c = \Gamma C(\rho) \log_2 D_{\text{eff}}$, in which black holes are treated as high-dimensional coherence structures. As mass decreases, dimensionality and internal coherence collapse, modifying the entropy flow and altering the radiation spectrum.

We present a toy model of black hole evaporation incorporating coherence collapse effects. Numerical simulation predicts a distinctive late-stage hardening of emitted radiation compared to classical Hawking spectra. This nonthermal spectral feature offers a potential observational signature, motivating future searches in primordial black hole evaporation, gravitational wave residuals, and laboratory analog systems.

Dimensional coherence collapse thus offers a novel thermodynamic resolution to aspects of the black hole information paradox and provides a testable framework for probing the informational structure of spacetime.

1 Introduction

Black hole evaporation, as originally proposed by Hawking [1, 2], introduces profound challenges to the foundations of quantum mechanics and thermodynamics. While the semi-classical treatment predicts a thermal radiation spectrum characterized solely by black hole mass, it leaves unresolved the question of how—or whether—information about the black hole's initial state is preserved. Attempts to reconcile unitary quantum evolution with Hawking radiation have led to proposals ranging from holographic encoding [4] to firewall hypotheses [5], yet a fully satisfactory physical mechanism for information transfer during evaporation remains elusive.

Here we propose that black hole evaporation is governed not solely by mass loss but by the progressive collapse of dimensional coherence within the black hole's information structure. By applying a thermodynamically motivated Coherence Equation, which relates entropy flow, coherence, and effective dimensionality, we show that black holes should experience a late-stage phase transition characterized by sharp coherence loss. This transition modifies the radiation spectrum, leading to a predicted hardening of emitted quanta relative to standard Hawking predictions. Preliminary toy simulations predict that this coherence-driven hardening may produce observable deviations in black hole evaporation spectra, with implications for primordial black hole searches and analog gravitational systems.

2 Coherence Collapse Framework

To formalize the role of coherence in black hole evaporation, we introduce the Coherence Equation, which relates the effective entropy flow H_c to three parameters: the entropy flow rate Γ, the system's internal coherence $C(\rho)$, and its effective dimensionality D_{eff}:

$$H_c = \Gamma C(\rho) \log_2 D_{\text{eff}}. \tag{1}$$

In this framework, a black hole is treated not merely as a mass-energy reservoir but as a high-dimensional coherence structure embedded within spacetime. As evaporation proceeds, both the mass M and the internal coherence $C(\rho)$ decline, leading to a collapse of the system's effective degrees of freedom. This collapse modifies the thermodynamic characteristics of emitted radiation, causing a deviation from the purely thermal spectrum predicted by Hawking. Specifically, as D_{eff} falls and $C(\rho)$ approaches zero, the entropy flow rate H_c spikes, implying a late-stage hardening of emitted quanta.

To explore the consequences of this model, we construct a simple numerical simulation in which a black hole evaporates according to standard mass loss laws, but with radiation temperature modulated by the coherence structure. We find that coherence collapse introduces a sharp and distinctive signature in the final stages of black hole evaporation.

3 Toy Model of Black Hole Evaporation

We model black hole evaporation beginning from an initial mass M_0 in natural units, with evaporation governed by the standard Hawking mass loss rate:

$$\frac{dM}{dt} = -\frac{k}{M^2}, \tag{2}$$

where k is a proportionality constant set by black hole surface area and radiation properties. The Hawking temperature at any mass M is given by

$$T_H(M) = \frac{1}{8\pi M}. \tag{3}$$

To incorporate coherence dynamics, we introduce a mass-dependent effective dimensionality $D_{\text{eff}}(M) \propto M^\alpha$ and a coherence function $C(\rho, M)$ that decays sigmoidally as the black hole mass approaches a critical value M_c. The resulting effective radiation temperature is modified by the Coherence Equation:

$$T_{\text{eff}}(M) = T_H(M) \times C(\rho, M) \log_2 D_{\text{eff}}(M). \tag{4}$$

We discretize the evaporation process in small time steps Δt and numerically integrate the mass, temperature, and effective temperature evolution until the black hole mass approaches the Planck scale.

4 Results

We simulate black hole evaporation beginning from an initial mass $M_0 = 5$ M_{Planck}, evolving according to standard Hawking mass loss. Figure 1 shows the mass decrease over time, exhibiting the expected slow early evolution followed by rapid collapse near the Planck mass scale, along with the corresponding temperature evolution.

The Hawking temperature shows a steady increase as mass diminishes, consistent with classical predictions. However, when coherence collapse is incorporated via the Coherence Equation, the effective temperature evolution diverges sharply from the standard model at late times. While initially tracking the Hawking temperature, the effective temperature exhibits a pronounced hardening spike as the black hole mass falls below $M_c \sim 2\ M_{\text{Planck}}$.

This late-stage hardening arises from the collapse of effective dimensionality $D_{\text{eff}}(M)$ and the decay of coherence $C(\rho, M)$. As these quantities decline, the effective entropy flow H_c increases sharply, amplifying the radiation temperature beyond Hawking predictions.

Figure 2 compares the final radiation spectra for standard Hawking evaporation and the coherence-corrected model. In the coherence collapse scenario, the radiation spectrum shows an excess at higher frequencies, deviating from the pure blackbody form expected under classical evaporation.

These results demonstrate that incorporating coherence dynamics into black hole evaporation predicts a distinctive observational signature: a late-stage, nonthermal hardening of emitted radiation. Such a signature, if observed in primordial black hole remnants or analog gravity systems, would provide evidence for the role of dimensional coherence collapse in gravitational thermodynamics.

5 Discussion

The results presented here suggest that incorporating dimensional coherence dynamics into black hole evaporation fundamentally alters the late-stage radiation process. Rather than a purely thermal and continuous evaporation terminating at the Planck scale, coherence collapse predicts a sharp hardening of emitted radiation due to entropy amplification as the black hole's internal coherence structure degrades.

This offers a potential new observational window into quantum gravitational phenomena. Specifically, deviations from the standard Hawking spectrum—particularly an excess of high-frequency radiation during the final stages of evaporation—could serve as a signature of coherence collapse. Detection of such deviations would not only modify our understanding of black hole thermodynamics but also support the broader hypothesis that information structure, not just mass-energy, plays a critical role in gravitational entropy dynamics.

While the toy model presented here captures the essential phenomenology, future work is needed to refine the quantitative predictions. More realistic collapse functions for $C(\rho, M)$ and $D_{\text{eff}}(M)$, as well as coupling to external spacetime degrees of freedom, could sharpen the predicted observational signatures. In addition, existing observational data—such as searches for primordial black hole evaporation signals, gamma-ray bursts, and gravitational wave post-merger noise—may already contain hints of coherence-driven deviations.

Finally, laboratory analog systems (e.g., acoustic black holes in Bose-Einstein condensates) offer a promising experimental platform for testing the coherence collapse hypothesis in controlled settings. These systems could allow direct observation of coherence loss effects during horizon evaporation-like processes.

In summary, dimensional coherence collapse provides a novel thermodynamic mechanism for modifying black hole evaporation, opening new pathways for testing the quantum structure of spacetime.

6 Conclusion

We have shown that dimensional coherence collapse during black hole evaporation predicts a late-stage hardening of emitted radiation, deviating from the standard Hawking thermal spectrum. Toy modeling demonstrates the plausibility of this effect, with potential observational consequences for primordial black hole searches, gravitational wave signals, and laboratory analogs. These results highlight the critical role of information structure in gravitational thermodynamics and motivate future experimental and theoretical investigations of coherence collapse phenomena.

Acknowledgements

The author gratefully acknowledges the assistance of multiple AI systems during the development of this work, including OpenAI's GPT-4, Anthropic's Claude, Google's Gemini, and DeepSeek-LLM. Their contributions in technical feedback, consistency checking, and manuscript preparation were valuable. The author takes full responsibility for all ideas, derivations, and interpretations presented.

Note: This is an example paper containing simulated data and theoretical predictions for illustrative purposes only. The figures referenced in this document represent conceptual visualizations rather than actual experimental results. This document was created to demonstrate the structure and content of a scientific paper on black hole evaporation theory.

References

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figures/evaporation_dynamics.png

Figure 1: Evolution of black hole mass and temperature during evaporation. The top panel shows mass decreasing over time following standard Hawking evaporation. The bottom panel shows temperature evolution, with the solid line representing standard Hawking temperature and the dashed line showing the effective temperature incorporating coherence collapse. Note the pronounced hardening spike in the effective temperature as the black hole approaches the Planck mass.

figures/radiation_spectra.png

Figure 2: Comparison of final-stage black hole radiation spectra. The solid line shows the standard Hawking radiation producing a smooth blackbody distribution. The dashed line represents the coherence collapse model, showing a characteristic hardening at higher frequencies. The observed excess of high-energy quanta in the coherence collapse model provides a distinctive observational signature that could be detected in primordial black hole searches or analog gravity experiments.